NASA TECHNICAL TRANSLATION NASA TT F-11,886

NASA TT F-11,886

A STUDY ON A MAXIMUM-SPEED WIND TUNNEL FOR RE-ENTRY INVESTIGATIONS

P. Nitsch, E. Riester, and N. Schmidt

Translation of "Studie uber eine Hochstgeschwindigkeits-Versuchsanlage für Wiedereintrittsuntersuchungen" Deutsche Forschungsanstalt Fur Luft-Und Raumfahrt (DFL), Deutsche Luft-Und Raumfahrt, Report 67-11, 28 pages, 26 April 1967

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 AUGUST 1968

TABLE OF CONTENTS

NASA TT F-11,886

A STUDY ON A MAXIMUM-SPEED WIND TUNNEL FOR RE-ENTRY INVESTIGATIONS

P. Nitsch, E. Riester, and N. Schmidt
Aeronautics Documentation and Information Center (ZLDI),
Jet Propulsion Institute*, Munich

ABSTRACT. The layout of a maximum-speed wind tunnel for re-entry conditions with sufficient running time and rather good simulation of real gas effects is studied. Recent test results concerning parts of the test facility are given. The installation of the test plant could be made most economical by using the hot-water supply of the DFL at Trauen as energy source for producing electric power and for the suction side of the tunnel drive.

1. Introduction

Much has been written about the need to investigate problems connected with the re-entry of space vehicles. We may therefore forego a repetition of these arguments. Furthermore, agreement may be assumed on the issue that in addition to the less expensive short-running-time wind tunnels such as shock tunnels, hot-shot tunnels, etc., quasi-stationary maximum-speed wind tunnels with sufficient running times and rather good simulation of the real gas effects are necessary. /7**

Such facilities have already been proposed by many authors. In 1961 the Jet Propulsion Institute of the DFL proposed such a test facility under the designation M 20-Kanal (M 20 wind tunnel). The facility represented a compromise with respect to the state of the art at that time. At that time it was believed that a post-acceleration based on the MHD principle had to be foregone and the latent heat should essentially be limited to that which is necessary to prevent the liquefaction of the air. The project was ultimately abandoned since a number of technical prerequisites had as yet not been satisfied and since the equipment had not been designed with sufficient versatility.

Another proposal was submitted by the IABG under the designation of ultra-high-speed wind tunnel. At that time the technical conditions were

*Prof. Dr. O. Lutz, Institute Manager, Dipl.-Phys. P. Nitsch, Dr.-Ing. E. Riester, Dipl.-Ing. N. Schmidt, authors.
**Numbers in the margin indicate pagination in the foreign text.

already much more favorable. The equipment had been desingned with a great deal of flexibility and accordingly was quite costly. During the discussions about this equipment the unanimous opinion prevailed that such a costly facility should be made available only once on a Federal Government level, should be planned with room for expansion and should take into account on an equitable basis the interests of research and industry.

This paper will make a proposal for a reworked maximum-speed test facility with the experience acquired since that time worked in as well as one in which the available subassemblies which are not being fully utilized are taken into account.

2. Layout Data /8

The layout data are determined from the flight envelopes for re-entry trajectories and from the minimum dimension of the measurement section which resulted from the model measurements and the free path lengths in the flow.

Figure 1 shows the position of the flight envelopes in the flight altitude-velocity diagram. The left-hand branch applies to the re-entry trajectories of earth satellites, the right-hand branch to the re-entry of lunar vehicles. To obtain an idea regarding the loads on the re-entry bodies, the static pressure and the static temperature are plotted in the diagram after a perpendicular shock wave. The ordinate contains on the right side scales for atmospheric pressure and temperature as a function of altitude, using as a basis the US standard atmosphere of 1962. Also plotted in Figure 1 is the flight mach number formed by the atmospheric temperature.

While Figure 1 reflects those data to which the re-entry body is exposed, Figure 2 contains in the same diagram with conditions applicable to re-entry simulation facilities: Latent pressure and temperature for isentropic shock or release of air under equilibrium and real conditions. Furthermore, the air throughput over a measurement cross section of 1 m^2 as well as the heating power and acceleration necessary are plotted. The abscissa also shows two additional scales for the latent enthalpy of the flight condition. The latent enthalpy in practice depends only on flight velocity. For simulation in the maximum-speed wind tunnel, we are interested in the common part of the flight envelopes ranging from a flight velocity of 3 to 8 km/sec. For flight velocities below 3 km/sec, a wind tunnel with an air heater using a plasma burner only will generally be sufficient. For higher velocities, an MHD section is necessary to obtain the additional enthalpy increase and acceleration. Figure 2 shows that the power for rather good simulation may be limited to about 50 MW/m^2 with extreme conditions not being considered. If we limit ourselves to a measurement cross section of 0.2 m^2 -- this is the minimum allowable cross section with regard to free path lengths of several millimeters --, up to about 10 MW power must be introduced in the air. Here, the power decreases slightly at lower flight velocities. The air throughput leads to values of 0.3 to 1 kg/sec, where /9
the higher figures again apply to lower flight velocities.

The required power of about 10 MW must be supplied by the plasma burner and by the MHD section jointly. While the plasma burner primarily results in a temperature increase, the gas is further accelerated in the MDH section whereby the pressure ratio necessary for the acceleration is reduced to tolerable values. From this we learn that the contribution of the MHD section at the line supply must be the greater, the higher the velocity to be simulated will be. On the other hand, the power to be introduced in the plasma burner varies little in the entire simulation range and will be slightly greater for lower flight velocities. The following chapters will therefore deal at first with the conditions and state of the art in the plasma burner and the possibilities of an MHD section will be evaluated subsequently.

3. Plasma Burner /10

The required control range for the plasma burner is relatively small. The air throughput can be easily varied by changing the neck cross section and the inlet pressure. The intended power range is about 4 to 8 MW where the upper limit applies to operations without MHD post-acceleration. In the design of the power supply, the power parameters must include the efficiency of the plasma burner. It is probably 50% or more.

For a plasma burner, two confingurations are available: "Flow across the arc" and "flow along the arc." According to data provided by Soehngen, much higher enthalpy values can be introduced in a flowing gas by using the latter configuration. Our own experiments with a plasma burner using the "flow across the arc" configuration have shown that high specific enthalpy values with a high efficiency can be introduced.

Figure 3 shows a sketch of the principle of this burner. The nozzle is at the same time the anode. The cathode foot of the arc is driven by a magnetic rotating synchronous field motor operating at 500 Hz. For currents above 200 amps, the arc fills the narrow cross section (diameter 5 mm) of the anode to a large extent so that the emerging plasma jet presents a favorable radial temperature distribution. The input flow at the anode is diffused. Difficulties result from controlling the high flow values at the cathode. The compact design of the burner insures a high efficiency. On the other hand, such a configuration requires optimum cooling of the components, particularly of the cathode. So far, operating times ranging from a minimum of 4 to a maximum of 18 minutes have been achieved. Using more intensive cooling methods, particularly at the cathode circuit of the light arc, additional increases in reliability and life were attained.

The following tabulation shows at what maximum addition of enthalpy and at what chamber pressure tests were conducted with the small experimental design of the plasma burner.

Mass flow (referred to neck cross section)	$\frac{g}{cm^2}$	16.5	41.0
Combustion Chamber pressure	kp/cm^2	2	5
Efficiency (referred to electrode power)		65%	80%
Enthalpy increase	$\frac{M\ joules}{kg}$	8.3	6.0

The contamination of the plasma by the burn-off of the electrode is less than 0.5 o/oo. /11

For lower enthalpy values, the burner has already been tested with pressures up to 11 kp/cm^2.

Figure 4 shows the variation in plasma burner efficiency as a function of the electrode power referred to the mass throughput. The fixed parameter for the horizontal family of curves is the mass throughput. Furthermore, the curves of constant enthalpy remaining within the gas are plotted on the diagram. It is shown that the power values required by the plasma burner to heat the maximum-speed wind tunnel are produced at high efficiency values.

Figure 5 shows the measurement and operational instruments for the plasma burner described.

Based on the results obtained so far it is expected that with the proper burner design for the flow, enthalpy values of 10 M joules/kg and more can be added by a plasma burner.

In order to maintain the radiation losses within reasonable limits, the arc must be surrounded by a high-density cold-gas jacket. This means, as a result of the high gas pressure connected therewith and the cross section contraction of the arc, that the burner must be operated at relatively low current (about 400 amps) and high voltage (1-5 kV). Due to the insulation problems which then arise at high temperatures it might be advantageous to limit the power of a burner. If higher power values are required altogether, the plasma jets of several burners may be combined.

In order to obtain maximum acceleration of the air in the maximum-speed wind tunnel by means of pressure gradients, a high latent pressure in the plasma burner is actually desirable. The production of the latent pressure offers no technological problem. It is best achieved as a supplement of the intermittently operating test unit by using a compressed-air reservoir.

The latent pressure is limited in practice by the jet losses which rise as a function of pressure within the plasma burner and by the entry conditions of the MHD section. Due to jet losses, the operating pressure in the plasma burner should not exceed 30 to 50 kp/cm^2. With respect to the MHD section, even lower latent pressure values within the plasma burner should be useful, especially at high simulation speeds.

Although the state of the art in the plasma burner permits a burner design suitable for maximum-speed wind tunnels, further research in this field of burner technology should be made: Control of the temperature load at the nozzle walls should be investigated to provide a reliable operation of the burner in the high-pressure and high-power range. /12

4. MHD Accelerator

The MHD accelerator, among other functions, represents the control mechanism for simulating flight velocity: The energy to be produced in the MHD accelerator varies as a function of flight velocity (3 to 8 km/sec) from 0 to about 20 M joules/kg. At our air throughput rates this corresponds to a maximum power of about 8 MW. In designing the power supply, the efficiency must also be taken into account for the MHD accelerator.

The conditions preferred at the MHD intake port (pressure about 1 atm absolute, temperature 3000° K min., velocity 1.5 km/sec min.) differed from the initial data of the plasma burner. Therefore, an intermediate expansion is required. In the intermediate expansion a compromise must be reached between the desired reduction of the pressure, the simultaneous increase in velocity and the detrimental decay of temperature. At about 3,000° K, air conductivity is so low that it must be raised by adding materials with a low ionization potential (e.g. Cs or K_2Co_x). At 3,000° the required amount of Cs is about 1% and thus the contamination is still tolerable. The MHD channel will have a square cross section of several centimeters on each side and will have a length of 1 meter in the direction of flow. In the MHD channel the velocity will be raised to 7 km/sec. Beyond the MHD accelerator the expansion continues. The added acceleration is relatively low (up to about 1 km/sec velocity increase); pressure and temperature are reduced for the expansion to the values to be simulated, the cross section of the flow is expanded to about 0.2 m^2 and the mach number is essentially raised by reducing the velocity of sound.

Regarding the technological configuration of the MHD section, the Jet Propulsion Institute of the DFL has no experimental data. Likewise, the technology of the MHD accelerators has not progressed anywhere else to the point where the data listed can be obtained easily. Therefore, additional research to improve the MHD accelerator for this application should be conducted, particularly to increase its efficiency. Nevertheless, it would make sense even now to design a maximum-speed wind tunnel with MHD accelerators since the facility can already be built, with several limitations regarding the simulation range. Provisions should be made for future expansion. /13

5. Power Supply

To provide adequate power for the plasma burner and the MHD accelerator, 20 MW dc current should be used. This power is sufficient for the simulation range presently being considered. At a later point in time this is somewhat short, particularly when the MHD technology will have progressed with respect to simulation, but not with respect to efficiency. At any rate, provisions to increase the power to about 30 to 40 MW dc current should be made. A facility with higher power values would be difficult to justify in our country for cost considerations. The required electrical power of 20 MW for the time being should be made available in the form of three-phase power to provide flexibility. Due to the transformer losses, about 25 MW three-phase power or mechanical-shaft power should be provided.

Three alternatives for the power supply are being discussed:

1. Public electric supply system, 2. Local power generation using nuclear energy, 3. Local power generation using hot-water turbine. Alternative 1 at first appears to create a minimum of problems. Public power starting at 100 kV from each line is always possible. The cost for take-off and transformer units may be considered relatively low compared to the overall project costs. Furthermore, lines several kilometers long up to the test area would not cause this method of supply to appear unreasonable. The inefficiency lies in the fact that a mains network designed for continuous consumption will be loaded down for several minutes with such a peak power load. In practice this will manifest itself in the cost of supplying power which at 25 MW will have to be budgeted for 0.6 to 3 million DM annually. /14
Local power generation based on nuclear energy should be considered insofar as the nuclear power plant at times other than during operational periods of the maximum-speed wind tunnel is available for other consumers and test purposes. A prerequisite for this is that the consumers, depending on the type invloved, are in a position to coordinate their operations. The decision should be made a function of whether there is a demand for an experimental nuclear power plant of the size projected.

The most efficient method for an intermittently operating test facility such as the maximum-speed wind tunnel is that which supplies power based on a storage principle. The storage medium capable of storing sufficient energy is hot water. Here, an existing hot-water supply unit with sufficient free capacity comes into view, namely that of the DFL in Trauen. It will be described in the appendix. It provides a jet power of 100 MW for a condenser pressure of 0.2 kp/cm^2 over a period of about six minutes. If we limit ourselves to an operating time of three minutes, half the stored amount of water is still available for other purposes (suction). The conversion of the jet power into electrical power is accomplished via a hot-water turbine and a generator. The hot-water turbine is still in its initial development stage. A 25% efficiency is feasible both technically and from a safety viewpoint, using the jet power as a reference. This insures the production of mechanical-shaft power of 25 MW. However, in order to use the hot-water energy economically it appears desirable to continue research in order to improve the turbine efficiency. Improvements from 10 to 30% could be made whereby the electrical power produced would increase to 35 - 50 MW or the hot-water consumption could be lowered accordingly.

If a hot-water turbine is used, the maximum-speed wind tunnel can no longer be considered independent of the site selected. If the DFL site in Trauen is selected, investments in public power supply equipment will rise to about 2.5 million DM. This amount does not include rectifier and control equipment. Hot-water power supply including turbine, condenser, generator, rectifier and control is preferable with an investment of 3 million DM. Furthermore, the current conversion costs are hereby eliminated.

6. Suction-Side Drive /15

The static pressure required in the measurement section, according to Figure 1, ranges from $5 \cdot 10^{-2}$ to 10^{-4} kp/cm^2, where 10^{-4} applies to the upper limit regarding flight altitude and speed of the common flight envelope portion. For the power and throughput parameters mentioned above, a static pressure of $3 \cdot 10^{-4}$ kp/cm^2 is sufficient.

The static pressure is by no means the pressure used as a basis for the design of the suction side, since behind the measurement section in the diffuser, pressure can be recovered. The pressure recovery in the diffuser for aerodynamic, supersonic and hypersonic wind tunnels lies in the order of magnitude of the pressure increase resulting from a perpendicular shock wave. Extrapolating these practical values to the maximum-speed wind tunnel, the pressure behind the diffuser would lie near 1 kg/cm^2, which, as a result of the relatively high boundary layer thickness can probably not be obtained. For a realistic diffuser pressure ratio of 30, a pressure of 10^{-2} kp/cm^2 results for which the drive on the suction side must be designed.

The tunnel drive on the suction side for maximum-speed wind tunnels should be as powerful as possible in order to make investigations on retro-rockets, etc. feasible. The use of jet pumps is recommended. A unit with multistage hot-water jet devices presents several major advantages: It is sufficiently powerful, economical in operation, price-worthy in manufacture and permits cooling the tunnel exhaust gases with cold-water injection. If the facility is built on the DFL site in Trauen, it can be connected to the hot-water supply already mentioned. The capacity of the hot-water supply is adequate to feed a multistage suction system of adequate design (up to 200 kg/sec hot-water consumption and up) in addition to the electrical power supply (consumption about 300 kg of hot water per second).

The hot-water jet pump is a relatively new alternative for extacting large volumes from low-pressure containers. Up until now, the relative long construction time of the hot-water supply was an obstacle to its popularity. Single-stage pumps for suction pressures starting at 0.1 kp/cm^2 have already proved their value in practice. Recently O. Frenzl detected satisfactory operational qualities in two-stage jet pumps with intermediate cooling by means of cold-water injection. Last year, research on two- and three-stage pumps started in the DFL, Trauen. The pumps were also fed by the hot-water supply already described. In their experimental design, the pumps were kept relatively small. Even better data may be expected fom a large scale design. /16

Figure 6 shows a view of the three-stage test setup. The ejectors are the tubes expanding in both directions, the last of which blows through the hall wall into the open. The two cylindrical vertical containers are intermediate water separators. The setup was operated at first with a given, certainly not optimum mixed-tube configuration. Furthermore, intermediate cooling between stages was foregone. However, the results clearly reveal the suitability of the device as the suction side of the maximum-speed wind tunnel.

Figure 8 shows the vacuum pressure as a function of the amount of air suctioned off (environmental temperature). The amount discharged increases with the dimensions of the unit at least quadratically. Figure 7 shows the corresponding hot-water throughput. The curves of both figures may be improved particularly by cold-water injection. From a comparison made by O. Frenzl on two-stage setups, a lowering of the hot-water consumption by at least a factor of two may be expected.

In order to be able to drive the maximum-speed wind tunnel as economically as possible, investigations on three-stage hot-water ejectors should be continued. The expenses incurred would be relatively small.

7. Results

A maximum-speed wind tunnel with sufficiently long measurement times and rather good simulation of the real gas effects can best be built by using the hot-water supply of the DFL, Trauen as the energy source. The power to be obtained from the hot water is sufficient for providing the current for plasma burners and MHD accelerators; practical data regarding most components of the facility are available at DFL.

According to the present state of the art, a facility must be built which does not yet include the complete simulation range, particularly regarding velocity. Furthermore, the facility in operation would still be beset by low efficiency. Therefore, additional research should be conducted on the following: /17

1. Plasma burners to obtain higher chamber pressures, higher power input values, higher specific enthalpy input values for the same service life and efficiency.

2. MHD accelerators to obtain higher power input values, higher specific enthalpy inputs and higher efficiency.

3. The hot-water turbine to obtain higher efficiency.

4. The hot-water ejector technology to obtain lower suction pressure and higher efficiency.

The maximum-speed wind tunnel, however, could now be designed with provisions for future expansion and built with a limited simulation range. Later on it could then be expanded to obtain the desired simulation range. The design of the facility as well as its construction and the experiments should be performed in cooperation between industry and research.

Appendix I

Description
of the Hot-Water Production and Storage Facility for the Ramjet Power Plant Altitude Test Chamber in Trauen

Application:

The facility is designed to drive an intermittently operating power plant wind tunnel of 70 x 70 cm^2 cross section at up to mach 3, a latent pressure of 1 atm, a running time of 7 minutes and a reheating time of about 3 hours. Since full capacity of the facility cannot be utilized within the foreseeable future by the wind tunnel, the possibility exists to provide other test chambers with hot water. Therefore, only the hot-water production and storage facility will be described.

Main characteristics:

Storage volume, 200 m^3

Hot-water pressure, 100 atm above atmospheric max

Hot-water temperature, 310° C max,

Hot-water output, 120,000 kg max,

Hot-water output flow, 500 kg/sec max with existing pipeline system, more if modified,

Time for reheating of the 120,000 kg, about 3 hours, potential unlimited continuous output about 10 kg/sec,

Start of operations of the facility: Late 1964, accomplished.

Hot-Water Storage:

The storage system consists of two $100 m^3$ reservoirs, based on production and assembly considerations. The reservoir dimensions are 2.80 m diameter and 18 m length each. To prevent cavitation during the water output their lower part remains 10 m above ground. The reservoirs are connected to each other by taps of 300 mm diameter, a return-line with pump which exchanges the water volume within about three hours and by a pressure equalization line in the steam chamber.

The reservoirs can also be tapped for other outputs:

1. At both output lines for a maximum diameter of 300 mm below the storage reservoir at ground level.

2. For smaller flow rates at the return line.

3. For flow rates of over 500 kg/sec, directly below these storage reservoirs up to diameters of 600 mm max. /19

If the hot water is to be moved in large pipelines or over long distances, a double line is recommended which may also be connected to the water return.

Heating Unit:

The core piece of the heating unit is a light oil-heated 20-ton-per-hour La Mont steam generator which furnishes the somewhat larger amount of saturated steam at 120 atm for heating purposes. The saturated steam is condensed in a heat-exchanger system mounted within the hot-water storage reservoirs whereby the unaffected storage water is being heated. The La Mont bypass system is driven with prepared water which may be supplemented with water from a local conditioning plant.

Since the heating facility is largely located in the open air, in addition to the drainage provisions for long interruptions in the operation, heat retainer and freezing protection devices were provided for winter operation as well as for short interruptions in the operations during the freezing season.

The heating facility can be controlled fully automatically or manually. The maintenance and monitoring units, most pumps and water preparation units are located in a large chamber.

Figure 1. Flight Envelopes in the Flight Altitude-Speed Diagram, Static Pressure and Static Temperature Following Perpendicular Shock With Equilibrium Conditions.

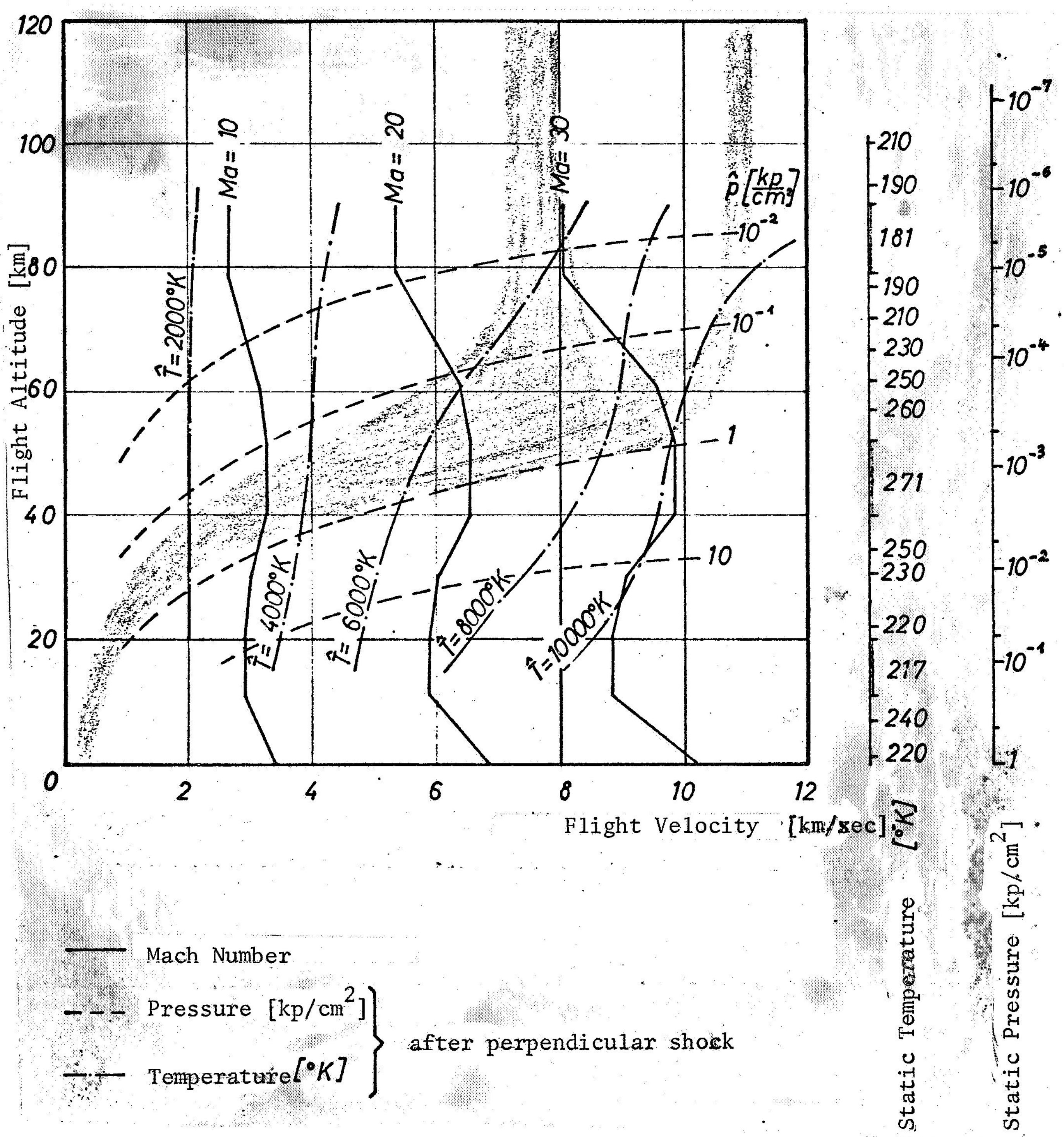


Figure 2. Layout Data For Simulation in the Flight Altitude-Velocity Diagram.

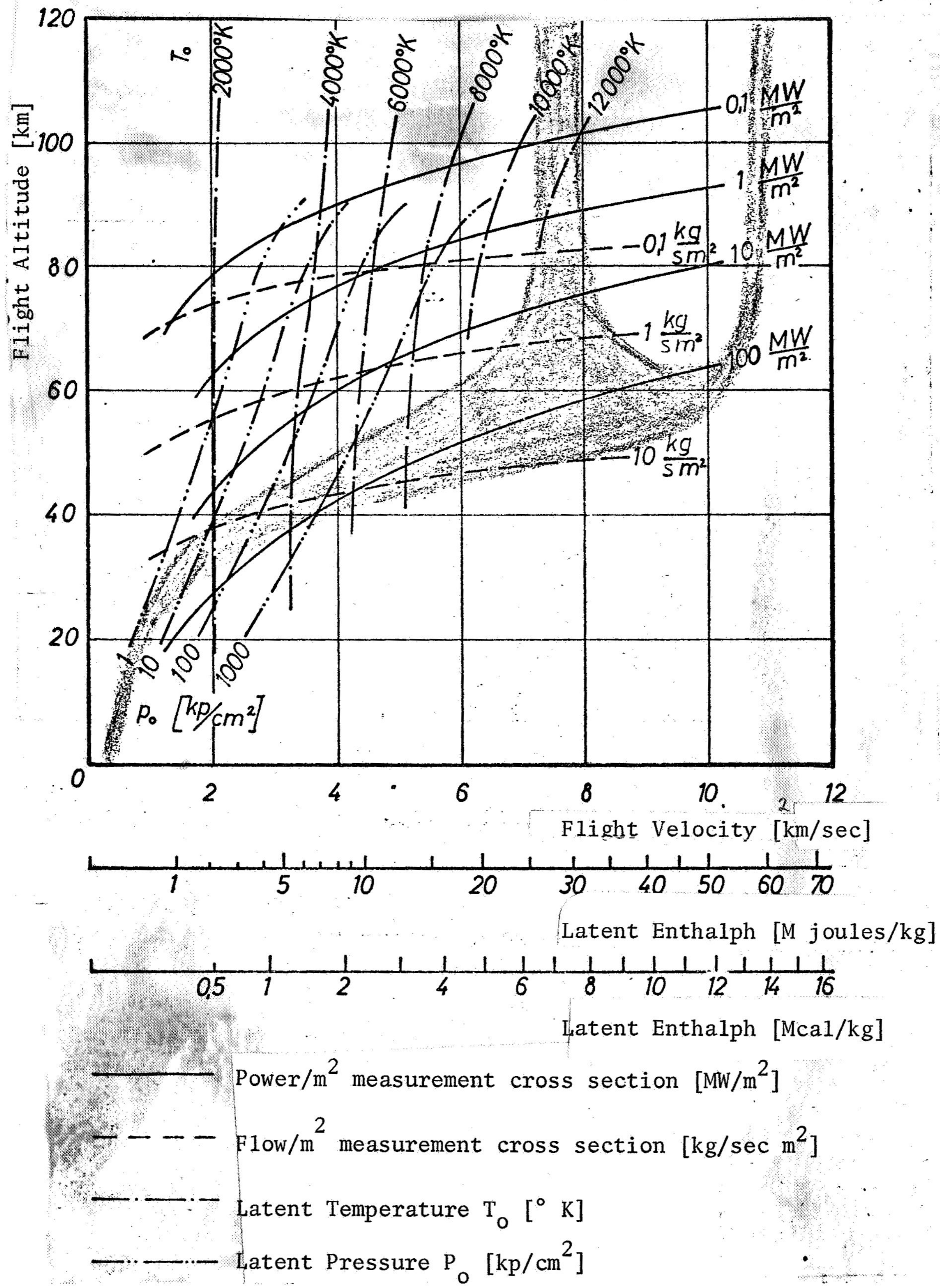


Figure 3. Schematic of a Plasma Burner for Air Heating. Laboratory Design up to About 80 KW.

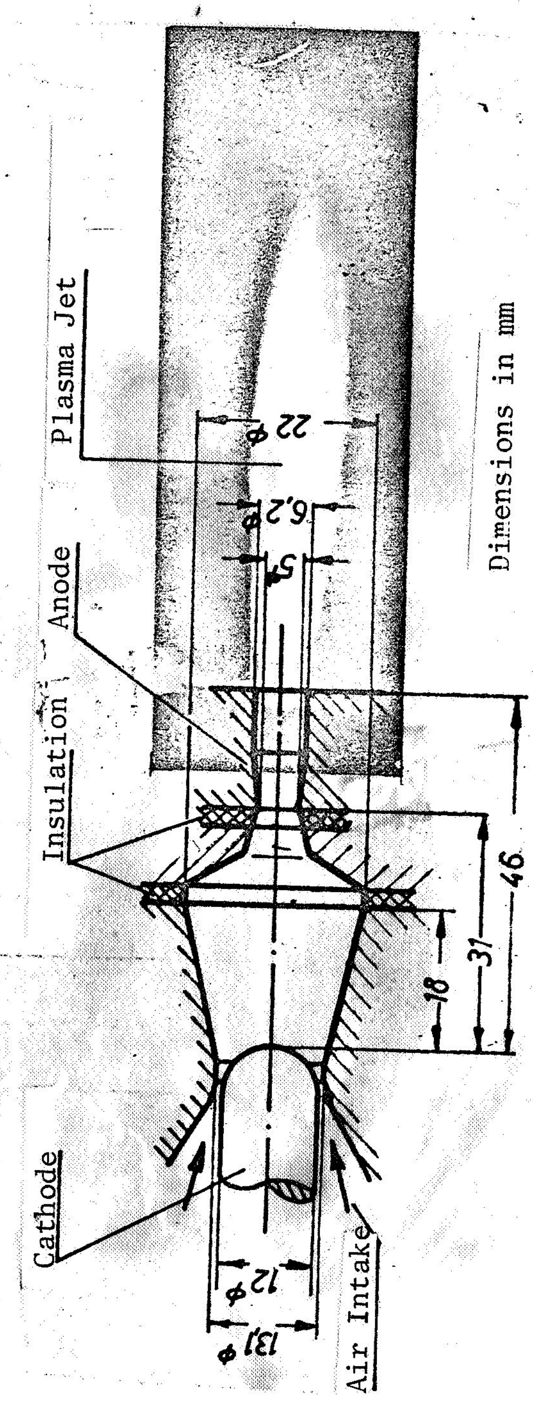


Figure 4. Efficiency and Enthalpy Increase of Plasma Burner (according to Figure 3).

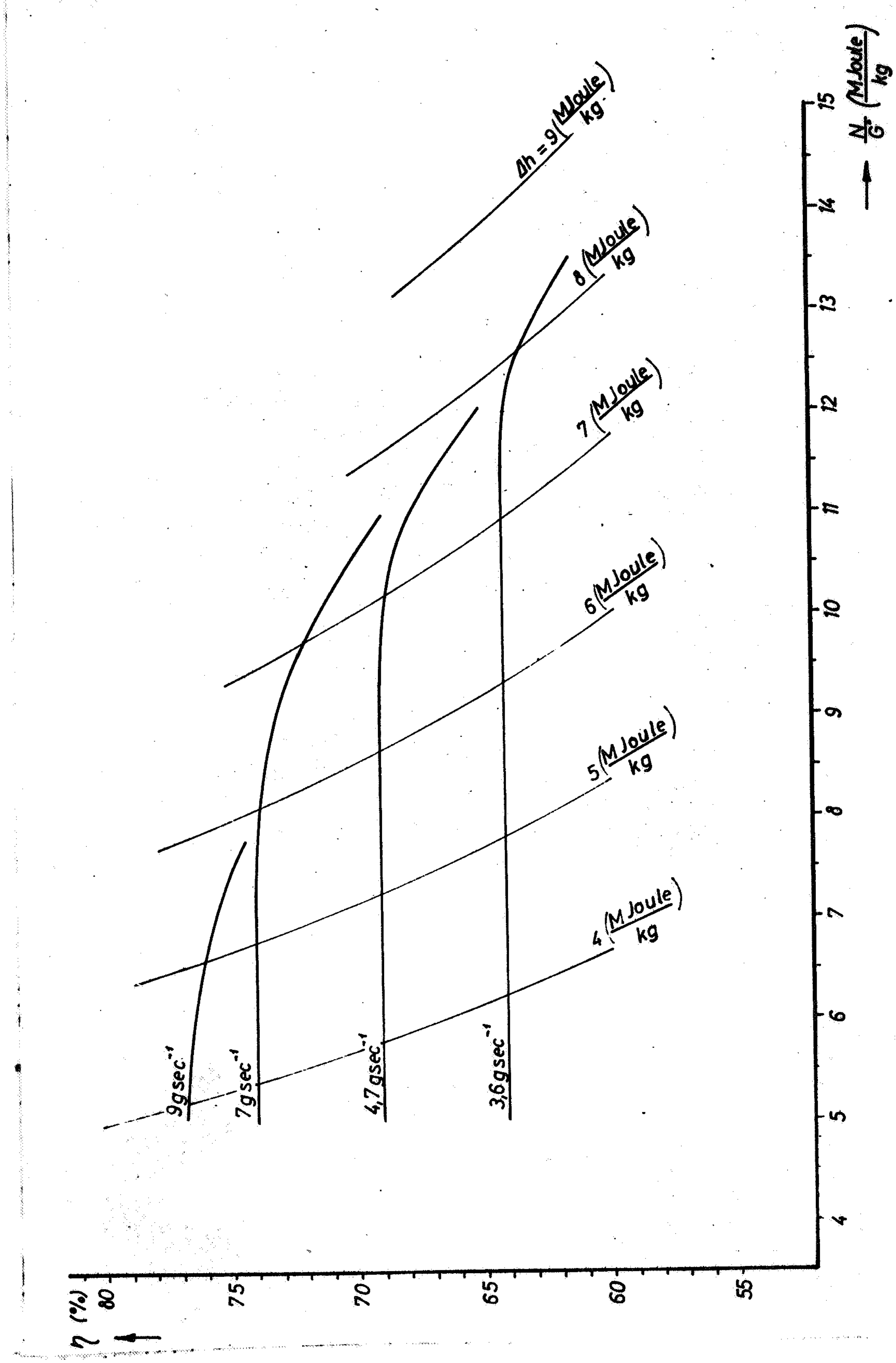


Figure 5. Control Panel, Power Supply (background) and Meters for Plasma Burner.

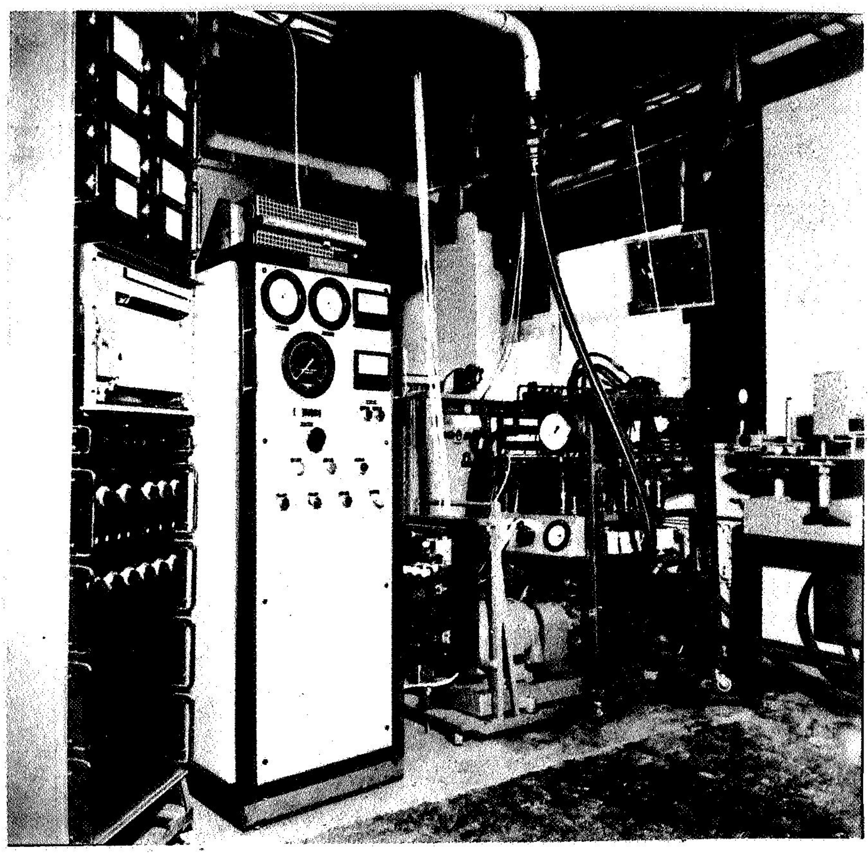


Figure 6. Three-Stage Test Ejector System of the DFL, Trauen.

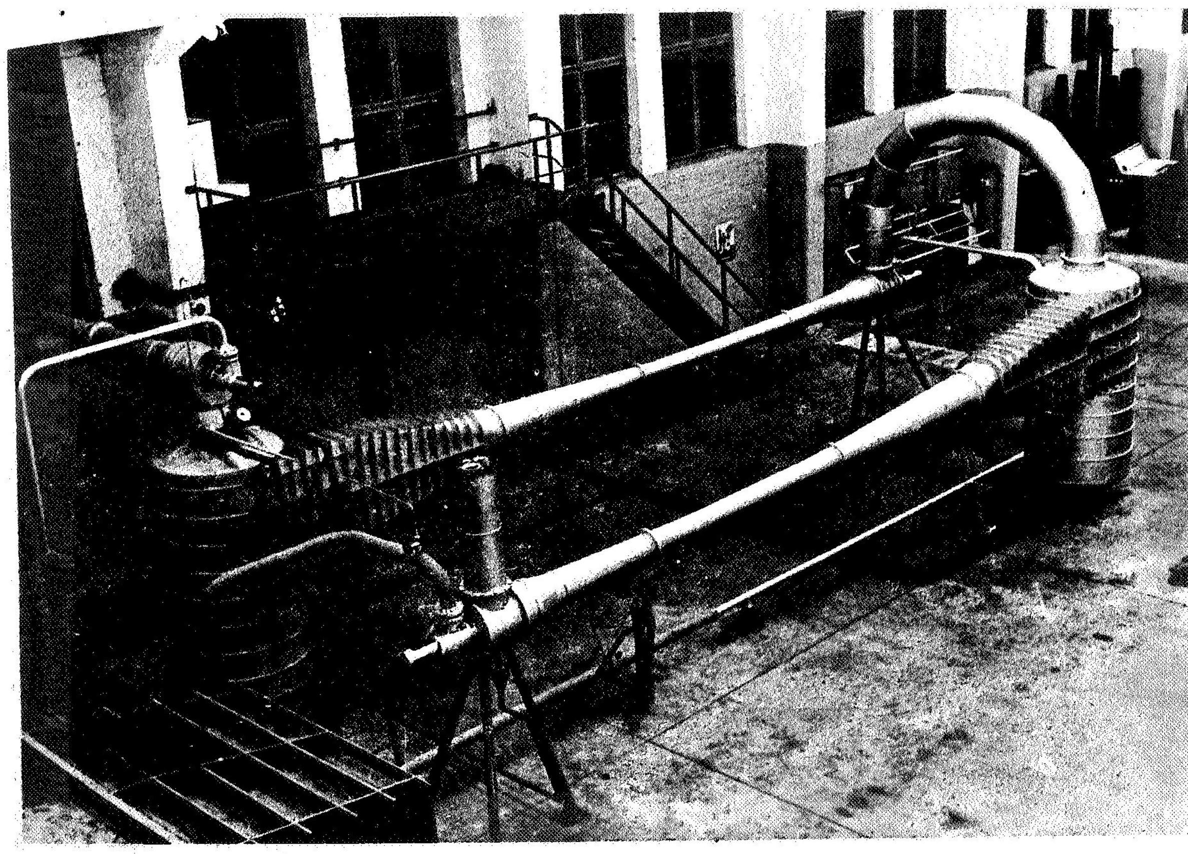


Figure 7. Hot-Water Consumption With Reference to Air Flow as a Function of Discharge Pressure Ratio for the Test Setup shown in Figure 6 (optimum values).

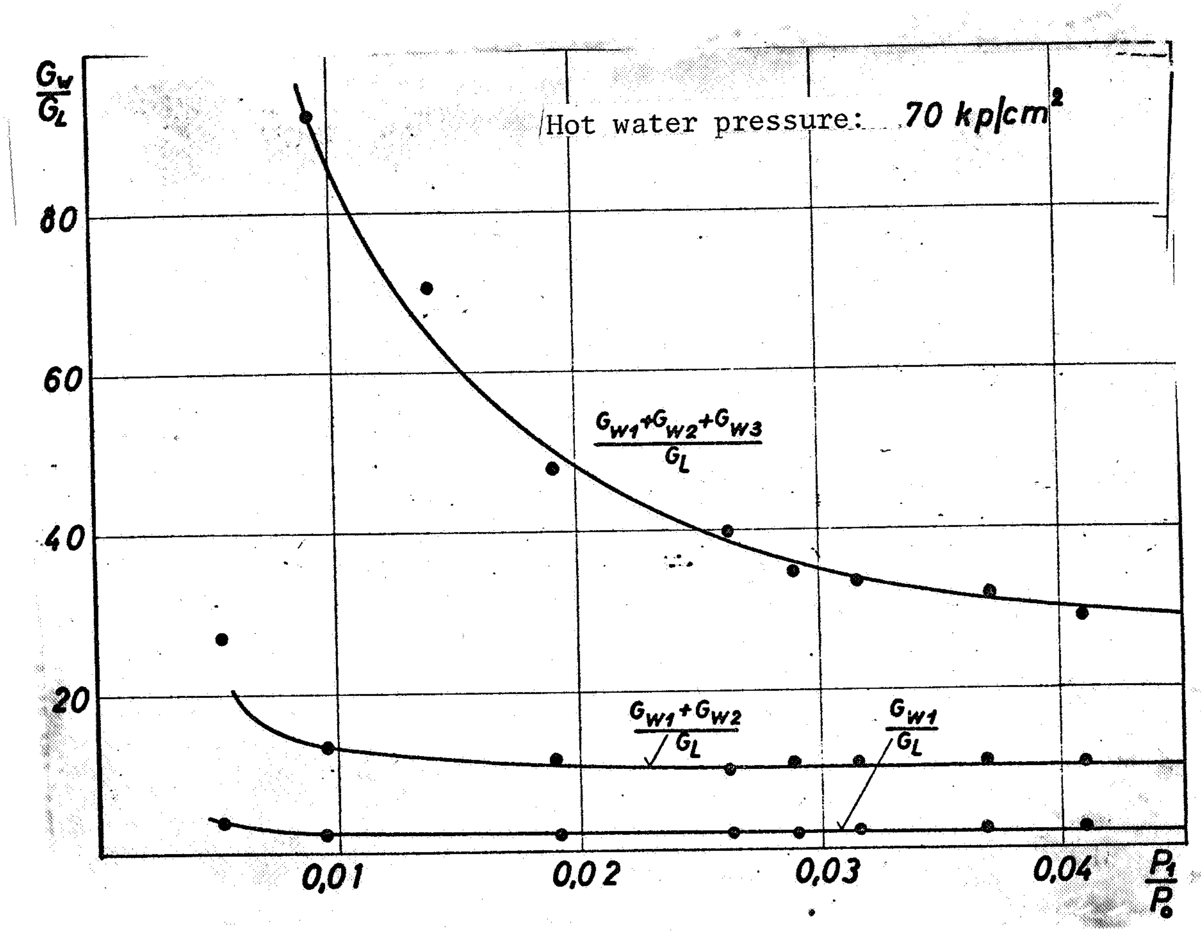


Figure 8. Optimum Discharge Pressure Ratio Attainable as a Function of Air Flow for the Test Setup Shown in Figure 6. Hot-Water Pressure 70 kp/cm^2.

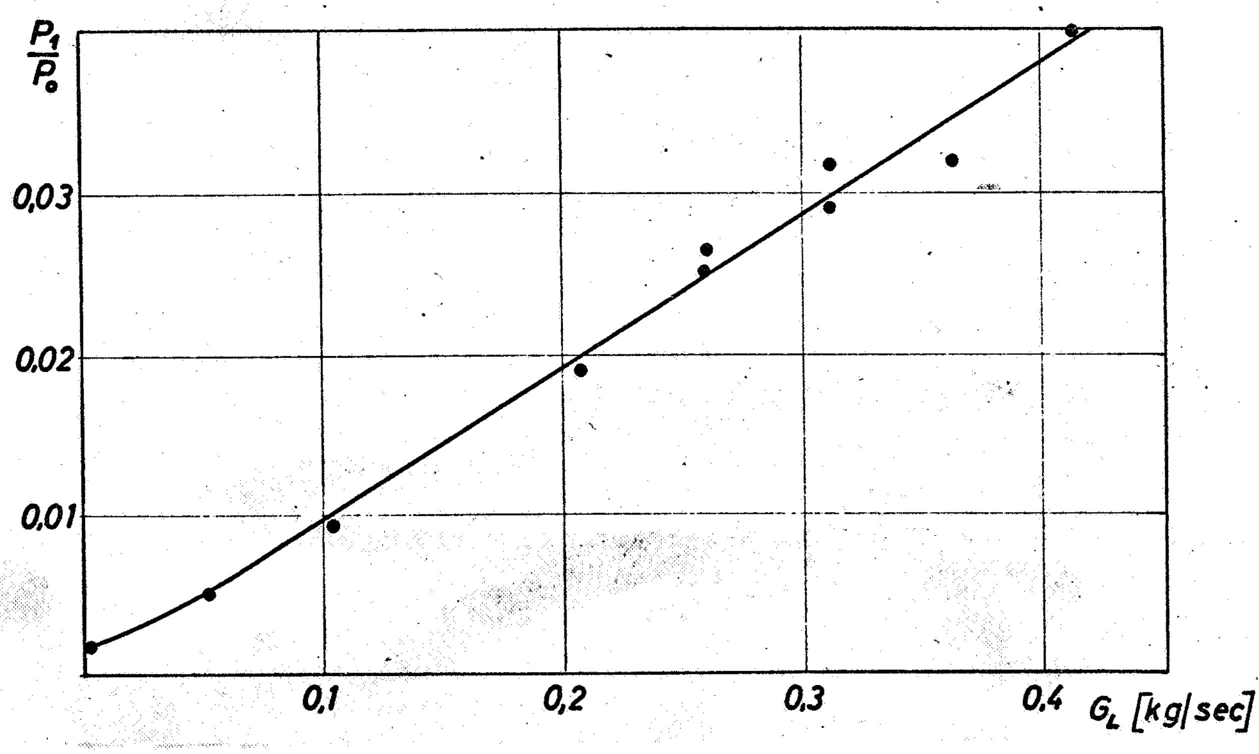
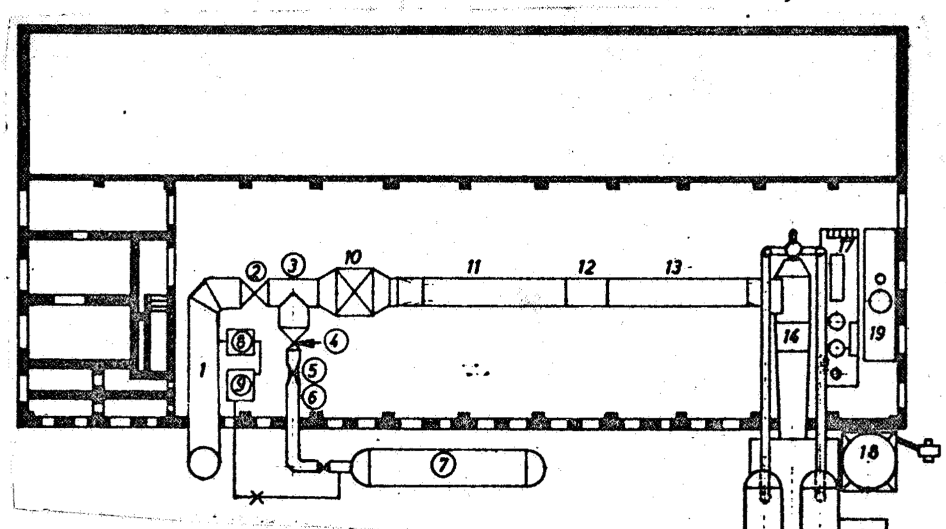
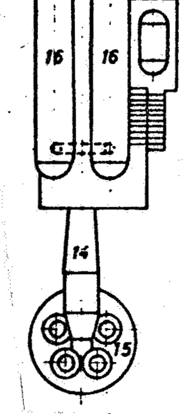


Figure 9. Ramjet Power Plant Altitude Test Chamber of the DFL, Trauen.

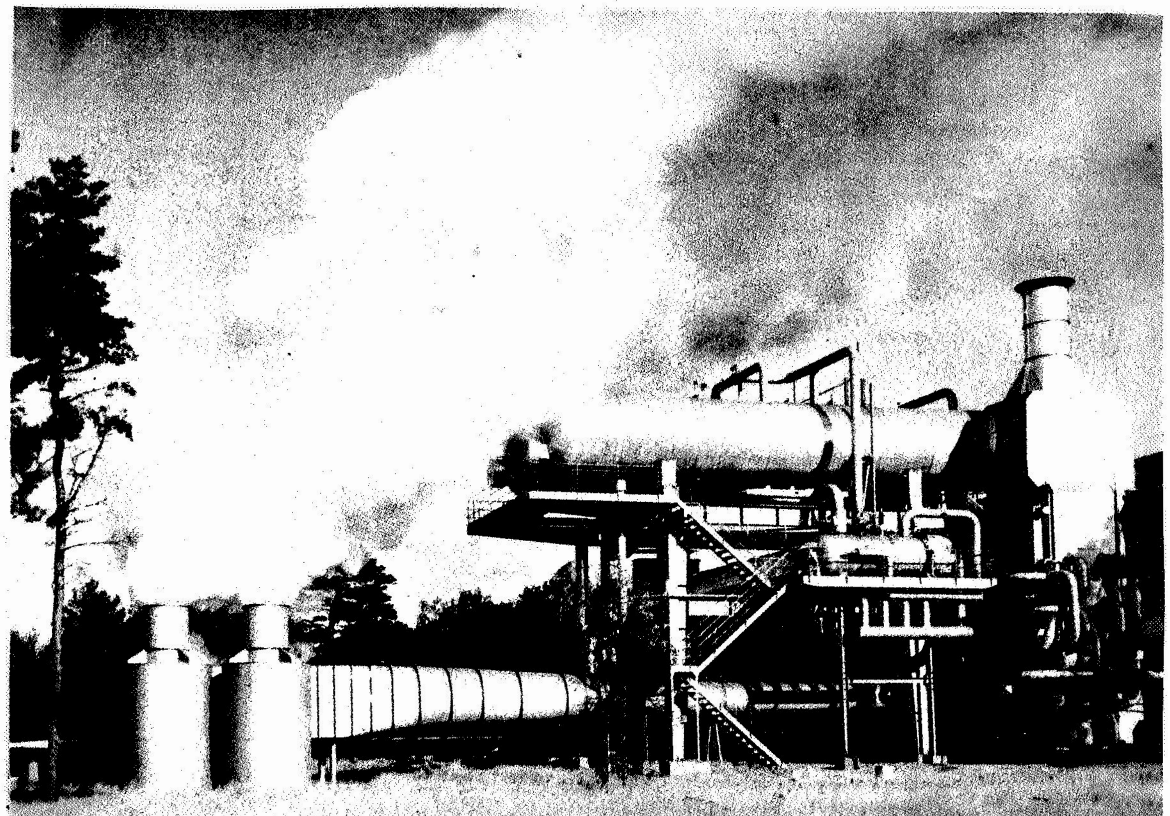




1. Suction Line
2. Blocking Valve 1,600 mm diameter
3. T
4. Control and Quick Shutoff Valve
5. Flow Limiter
6. High-Pressure Line with Flow Compensation
7. Compressed Air Storage Tank 100 atm above atmospheric, 80 m^3
8. High-Pressure Compressor
9. Dryer
10. Air Heater
11. Nozzle
12. Measurement Chamber
13. Diffuser
14. Hot-Water Ejector
15. Water Separator
16. Hot-Water Storage Tank 100 atm above atmospheric, 200 m^3, 310° C
17. Pump Trough
18. Steam Generator 20 tons/hour
19. Water Preparation

Items provided with 0 are part of the pressure side. Items 16 to 19 are part of the hot-water supply.

Figure 10. Hot-Water Supply and Large Ejector of the DFL, Trauen.



Translated for the National Aeronautics and Space Administration under contract No. NASw-1695 by Techtran Corporation, P. O. Box 729, Glen Burnie, Maryland 21061